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This report discribes recent analytical and experimental results on nonlinear control of systems with simultaneous magnitute and rate saturations.

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Nonlinear Control of Mechanical Systems in the Presence of Magnitude and Rate Saturations

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This project is aimed at developing systematic techniques for control of mechanical systems in the presence of magnitude and rate saturations, with particular emphasis on problems arising in the context of high performance aircraft. Magnitude and rate saturations are a major source of nonlinearity in all flight control systems and are a fundamental mechanism of instability in both automated and piloted flight. Recent theoretical developments in nonlinear control theory as well as increasing computational power in offline and online computation are enabling the use of more powerful techniques for control of these systems. This project builds on an established base of work in nonlinear control of mechanical systems and stabilization of strongly nonlinear systems to explore new approaches to this problem. In addition to developing theoretical tools for analysis of flight control systems with saturations, experimental validation of the techniques is being performed using a flight control experiment at Caltech that exhibits many of the essential features of aircraft systems while remaining simple enough to allow meaningful testing of fundamental feedback mechanisms.

Our results to date have focused on two different approaches to modifying high performance control laws to maintain stability and performance in the presence of rate saturations. The first approach is the use of a nonlinear gain scheduling technique that degrades the performance of the system when actuators are saturated in such a way as to insure stability. Experimental results on the Caltech ducted fan show this approach to be very promising and these results will be presented at the AIAA Guidance, Navigation, and Control conference in August, 1997 [1]. Analytical results have been derived giving proof of convergence of the algorithm and indicating how and why the controller works [2].

The second approach that we have been pursuing is the use of homogeneous control techniques to convert a linear controller into a nonlinear controller that obeys magnitude and rate limits. This follows an idea based on the work of Praly (in France) and also builds on previous work at Caltech in the construction of homogeneous feedback laws. To date, we have made some progress on applying these ideas to linear systems that are marginally stable (no unstable eigenvalues) and are continuing to develop these techniques and understand how to apply them. The goal of this approach is to design controllers that can "wrap around" existing controllers to allow operation in the presence of magnitude and rate limits and we expect further progress in the coming year.

In addition, we have collaborated with Professor Andrew Teel at the University of Minnesota to test some of his controllers on our flight control experiment. Teel has developed techniques for combining local, high performance controllers with global, stabilizing controllers. These stabilizing controllers have poor performance, but can stabilize the system in the presence of actuator limits.

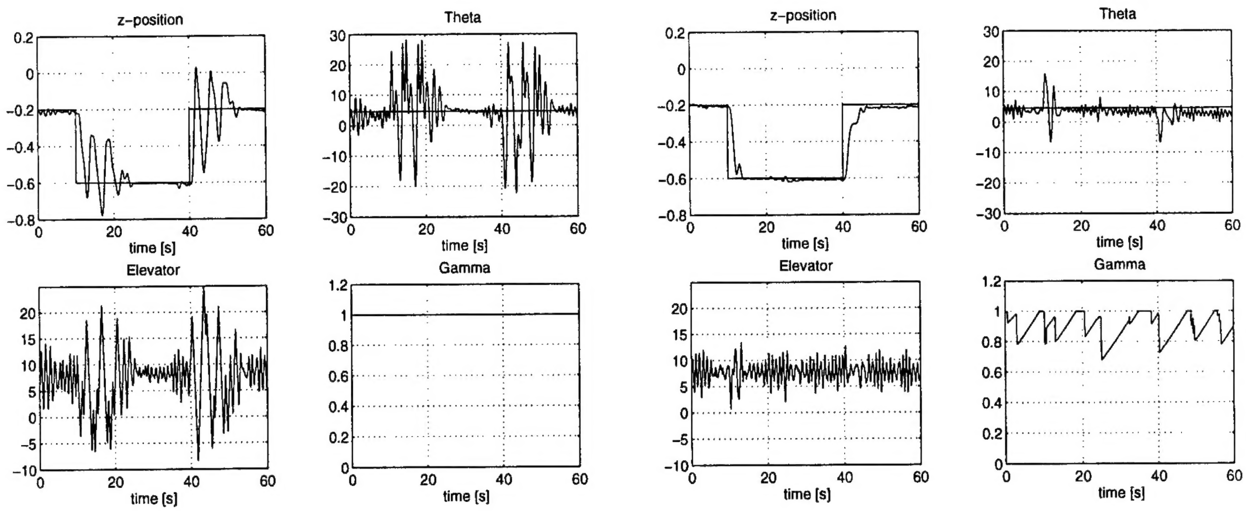

Figure 1: Experimental results on the Caltech ducted fan experiment. Left: linear controller with 20 deg/sec rate limit. Right: nonlinear scheduling control law (Lauvdal, 1996).

As a consequence, it should be possible to achieve very good local performance using aggressive control designs while maintaining stability of the system at the operating envelope. Experimental testing of these controllers has demonstrated the efficacy of the approach as was recently presented at the 1997 American Control Conference [3].

Finally, we are beginning to pursue the development of real-time trajectory generation techniques in the presence of magnitude and rate saturations. At the present we are limiting ourselves to so-called differentially flat systems, which are nonlinear systems for which trajectory generation is conceptually simple and computationally tractable. This work is just beginning and we have not achieved any significant new results to date, but we are expecting this to be a very fruitful avenue of research with many applications to aerospace systems.

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